Carrier-Envelope Phase-Dependent Coherence in Two-Level Systems Interacting with Few-Cycle Pulse Pairs

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Abstract: We report a numerical study of the carrier-envelope phase-sensitive population inversion and polarization in two-level systems interacting with few-cycle optical pulse pairs.
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1. Introduction

With the fast growing interest in both theoretical and experimental study of ultrafast dynamics in quantum systems, it has been shown that some of the few-cycle related phenomena in two-level systems are not only dependent on the pulse envelopes and carrier frequencies but also sensitive to the carrier-envelope phase (CEP) φ_{CE} [1]. This renders the implication of possible semiconductor-based CEP detection, which potentially holds a number of advantages over the CEP-probing techniques currently available [2–4]. Here we seek to take one step further in the quest of CEP-sensitive dynamics by exploring the coherent interactions between a two-level system and a few-cycle pulse pair. Although pulse pairs interacting with two-level systems have been extensively studied in the context of quantum communications [5–7], little attention has been given to few-cycle pulse pairs. In the few-cycle regime, the rotating wave approximation (RWA) commonly used to simplify the theoretical model is no longer valid and strong coupling between the two-level system and the field has to be assumed [8]. The present work focuses on the coherent response of a two-level system to the pulse pair and demonstrates constructive and destructive interferences between the pulse pair and the two-level system. Our result shows that the carrier population inversion (a detectable quantity) is a direct consequence of the interference, which is highly sensitive to the CEP of the two pulses. This provides a potential path toward direct CEP probing.

2. Theoretical Frame Work

Our simulation are based on the interaction model of electrical field and a two level system, which means Bloch equations without RWA but within the dipole approximation [9]. The Bloch equations can be written as [10]:

$$\dot{u} = \Omega v - \frac{u}{T_2} \tag{1}$$

$$\dot{v} = -\Omega u - 2\Omega_R(t)\omega - \frac{v}{T_2} \tag{2}$$

$$\dot{\omega} = 2\Omega_R(t)v - \frac{(\omega+1)}{T_1} \tag{3}$$

where u, v, ω represent the real part of the polarization (i.e. dispersion), the imaginary part of the polarization (i.e. absorption), and the population inversion, respectively. The overdot denotes the time derivative. T_1, and T_2 are spontaneous decay time and dipole dephasing time, respectively. Since comparing to typical values of T_1 and T_2, the pulse durations and the relative pulse delay used in our simulations are negligibly small, the terms associated with T_1 and T_2 are neglected in the current study. Ω represents the transition frequency of the two level system. $\Omega_R(t)=\mu E/\hbar$ is the Rabi frequency. We use sinc-shaped pulses for its good representation of few cycle pulses [11]. By solving the Bloch equations numerically, we obtained the phase-dependent dynamics between the few cycle pulse pair and the two level system.

3. Simulation Results

Fig.1 shows the population inversion ω versus time under a destructive condition (Fig. 1(a)) and a constructive condition (Fig. 1(b)). Five femtosecond pulses are used in both cases and the relative pulse delay is set at 20 fs. In the case of Fig. 1(a), proper parameters (including the CEP and the amplitudes of the two pulses) are chosen so that the population inversion reaches the maximum (+1) after the first pulse but switches to the minimum (-1) after the second pulse. Whereas in Fig. 1(b), the population inversion stays at the initial condition (-1) after the first pulse but jumps to the maximum after the second pulse.

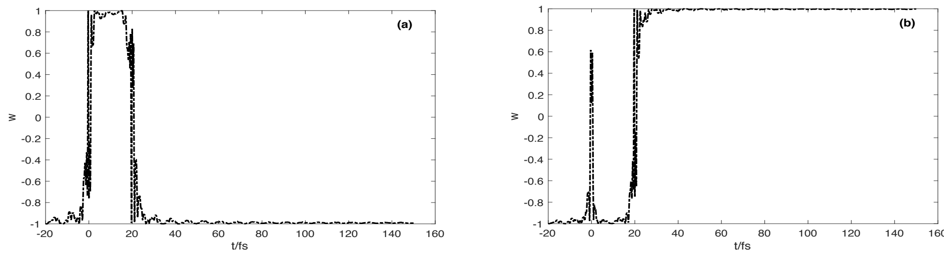

Fig.1. The population inversion induced by a 5-fs pulse pair. a) Inversion changes from -1 to +1 and then back to -1; b) Inversion changes from -1 to -1 and then to +1.

Fig.2 further demonstrates the fact that the behaviors of the inversion is caused by coherent interference between the two pulses and the two-level system. Fig. 2(a) shows the time evolution of u under the same conditions as Fig. 1(a). The significant reduction in the oscillation amplitude of u indicates a destructive condition between the polarization of the two-level system and the second pulse. Similarly, Fig. 2(b) shows the time evolution of u under the same conditions as Fig. 1(b). The significant increase in the oscillation amplitude of u indicates a constructive condition between the two-level system and the second pulse. Our simulation has shown a strong dependence of the interference outcome on the CEP of the two pulses. This is further demonstrated in Fig. 2(c), where ω is plotted against the CEP and the amplitude of the pulse pair. It is clear the imprint of the first pulse in the two-level system interacts coherently with the second pulse, leading to a CEP-sensitive inversion. This can be a useful effect for potential CEP detection schemes.

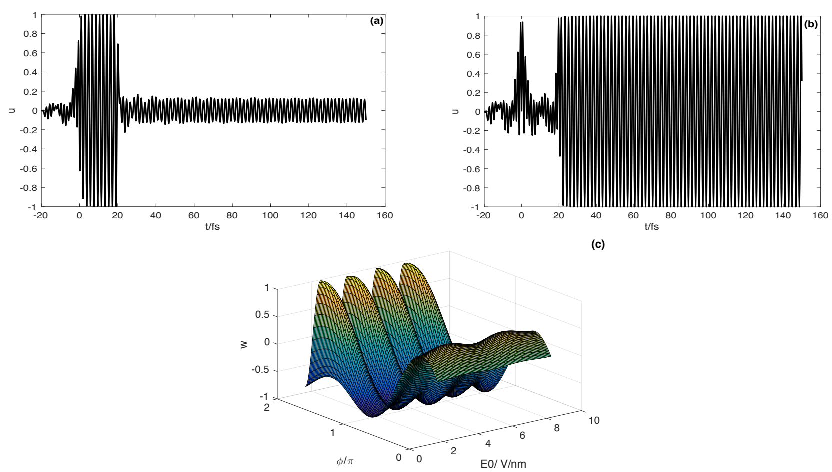

Fig.2. CEP-dependent behaviors of u: a) destructive interference case; b) constructive interference case; and c) the dependence of ω on the CEP and the amplitude of the pulse pair.

4. References

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